Tevatron results on heavy flavour production and decays

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On behalf of the CDF and D0 Collaborations

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Outline

The most recent Tevatron results on heavy flavor production and decays

== > only b hadrons

- B mesons:

  rare decays : $B_s \to \mu^+\mu^-$ (see also F. Ligabue, HF 2 session)

  B_c semileptonic decays : $B_c^+ \to J/\psi\, \mu^+ \nu$

  orbitally excited B mesons : $B_1^{0,+},\ B_2^{*0,+},\ B_{s1}^0,\ B_{s2}^{*0}$

  new $B\pi$ resonances : $B(5970)^{0,+}$

- b baryons : $\Xi_b^{0,-},\ \Omega_b^-$ (J/ψ and fully hadronic modes)

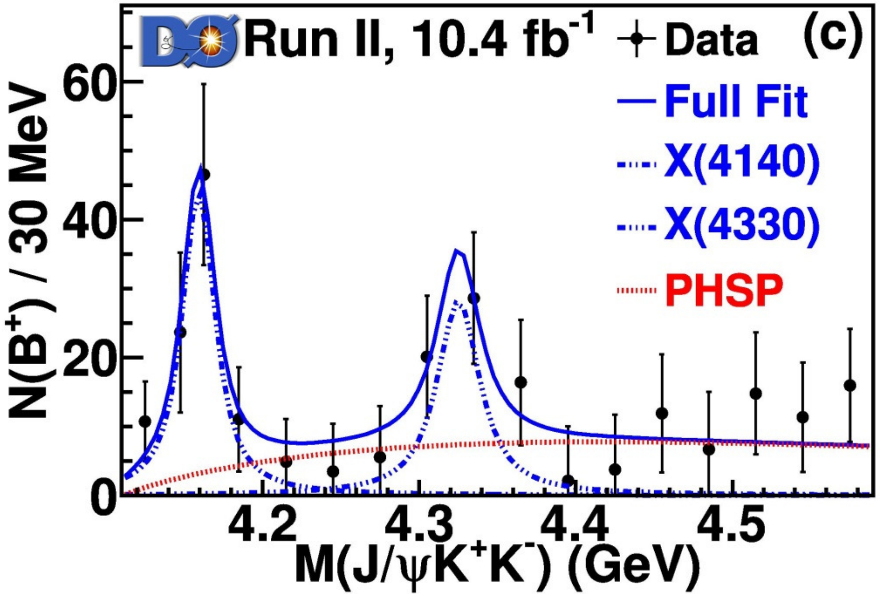
- Exotic resonances : X(4140)

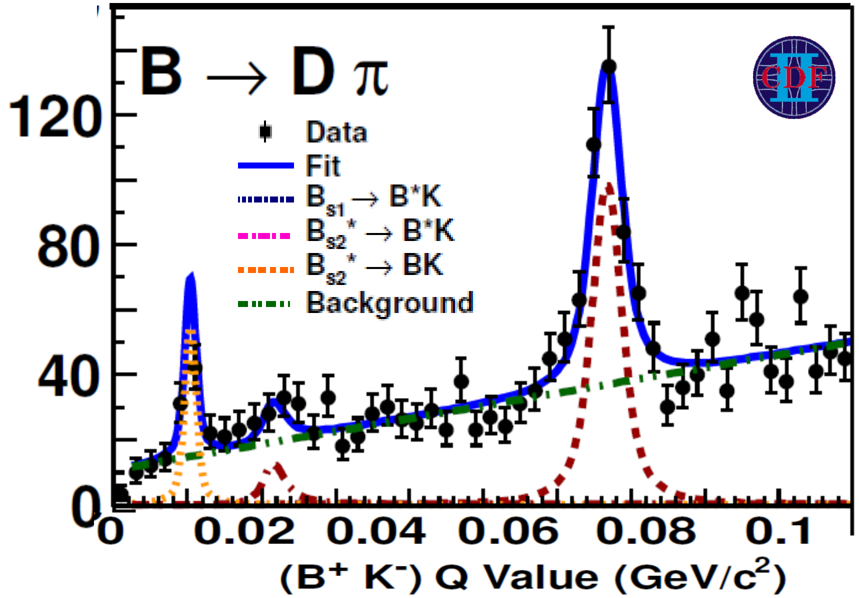
See also: http://www-d0.fnal.gov/d0_publications/d0_pubs_list_bytopic.html
http://www-cdf.fnal.gov/physics/new/bottom/bottom.html
S. Donati – talk at "Rencontres de Moriond – EW" 2014
M. Kambeitz – talk at "Rencontres de physique de la Vallée d'Aoste" 2014
M. Williams – Fermilab theoretical-experimental seminar, Oct. 18, 2013

B Trigger types at Tevatron

CDF and D0	CDF	CDF
Di-muon (J/ψ)	Displaced track +1 lepton	2-track trigger
$P_t(\mu) > 1.5$ GeV/c	P_t(lepton) > 4 GeV/c	P_t(track) > 2 GeV/c
J/ψ modes	d_o(track) > 120 μm	d_o(track) > 100 μm
	Semileptonic modes	Fully hadronic modes

(not used in the following)

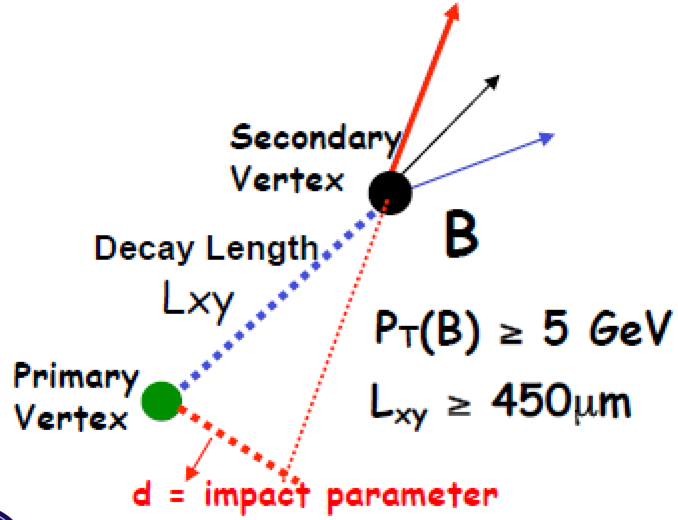


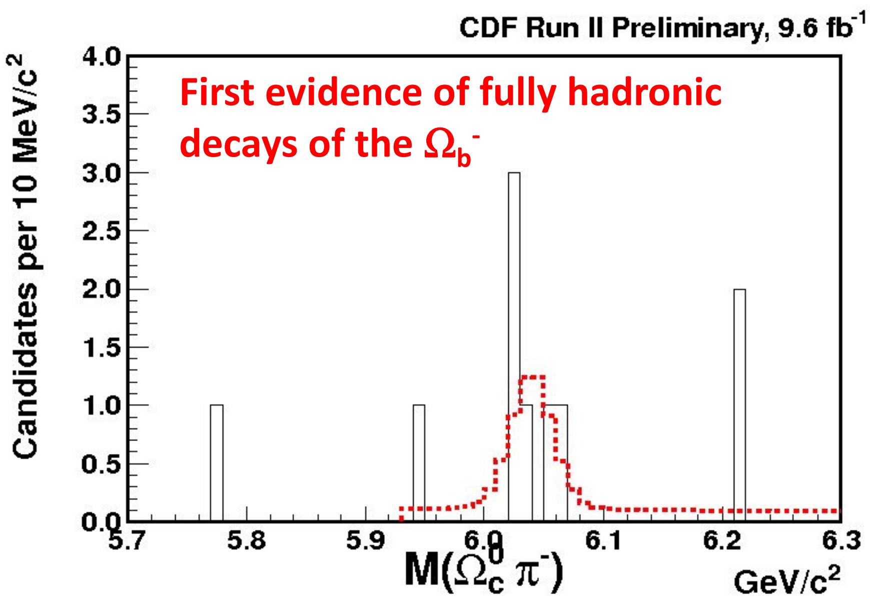


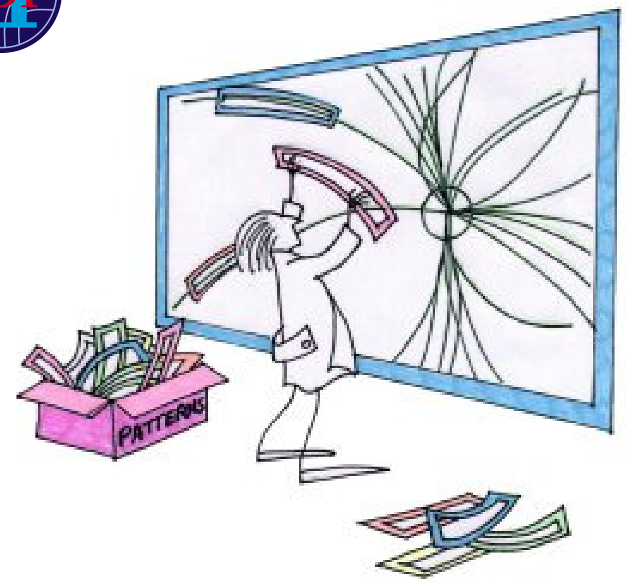
A special tool for reconstructing secondary verteces : CDF-SVT

The CDF Secondary Vertex Trigger (SVT):

- a unique powerful tool for easier access to to the full hadronic modes of the B-hadrons;
- based on recognition of tracks diplaced w.r.t. the primary vertex from pre-loaded patterns (AM, Associative Memories);







B-meson rare decays: the case of the $B_s \rightarrow \mu\mu$

A long search at Tevatron; in more than 10 years a variety of methods and tools was developed, having outlined the main road for the LHC evidence results ….

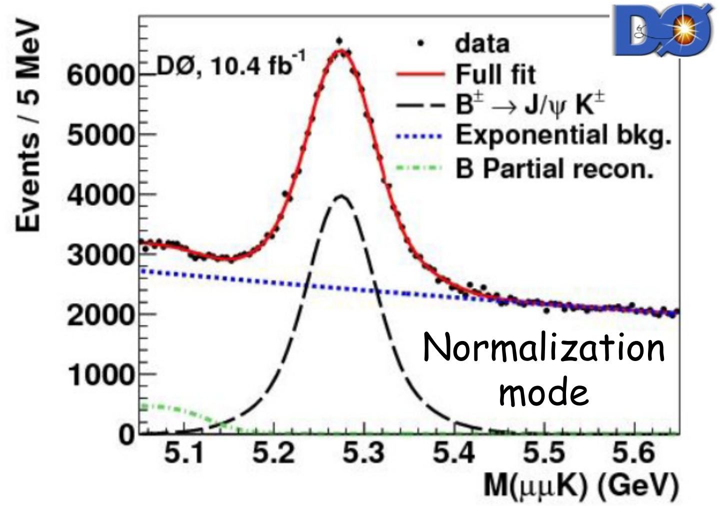
- High purity and efficiency selection of di-muon and reconstrcuted B^+ samples

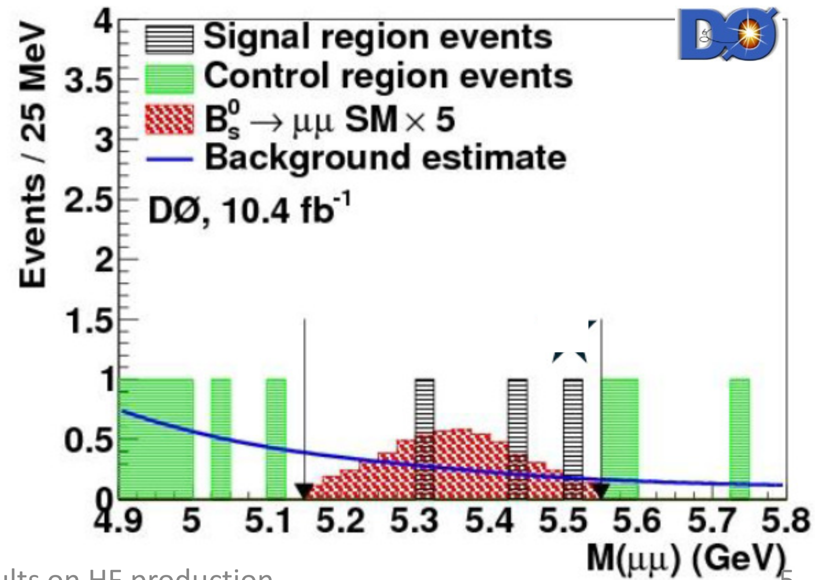
- High rejection of the background by applying multi-variate analysis techniques (Neural Netwok, Boosted Decision Tree,…)

- Single Event Sensitivy (SES) determined from the normalization mode :

$B^+ \rightarrow J/\psi K^+ \rightarrow (\mu^+\mu^-) K^+$

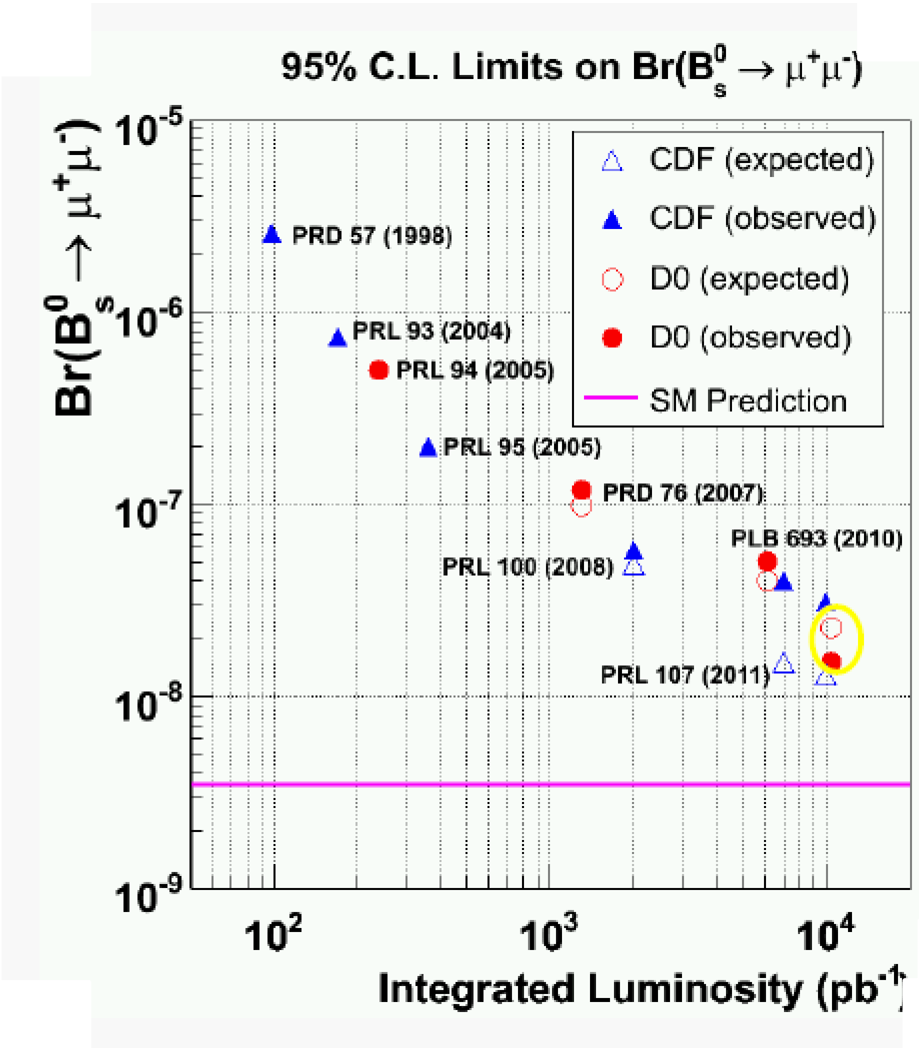
- Bayesian and frequentist approches to set the expected (from SES) and observed limits at 90% (95%) C.L.



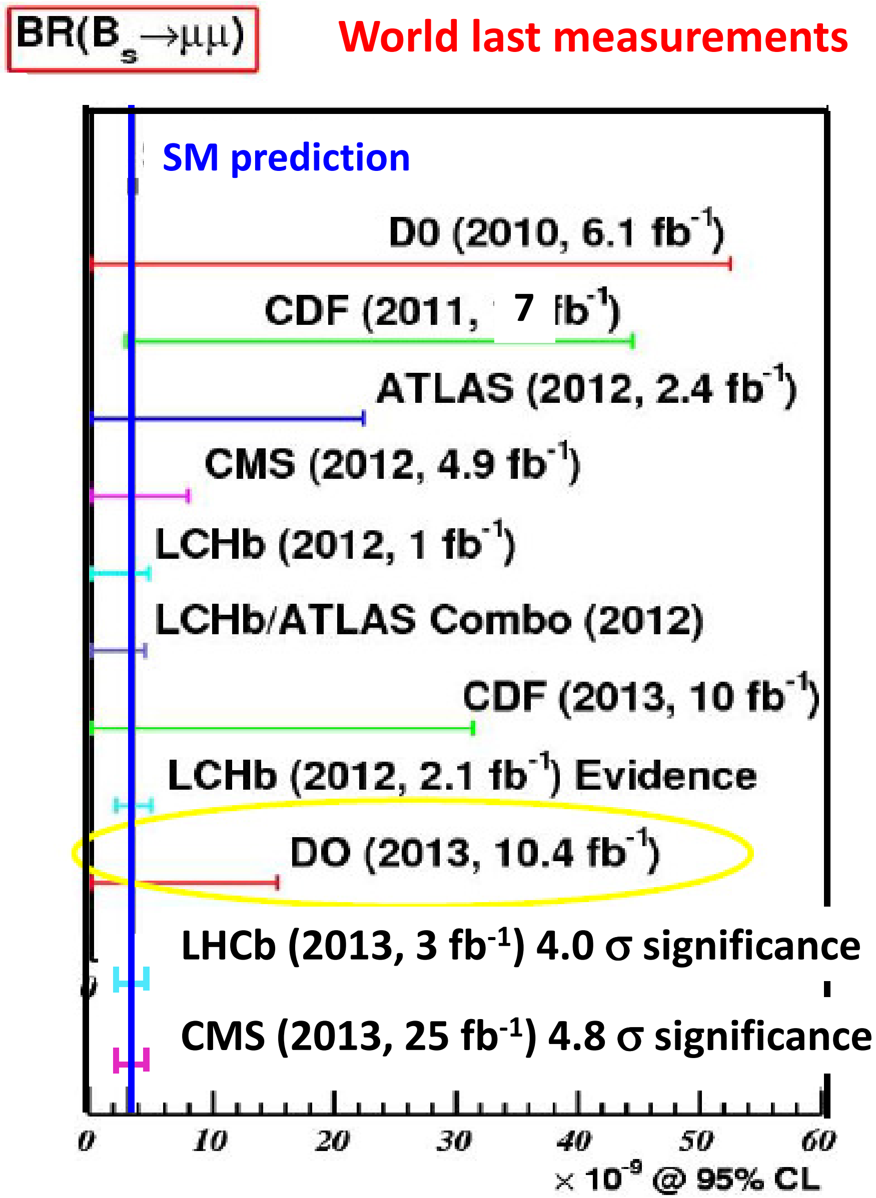


$B_s \rightarrow \mu\mu$ result summary

Tevatron history (run I and run II)



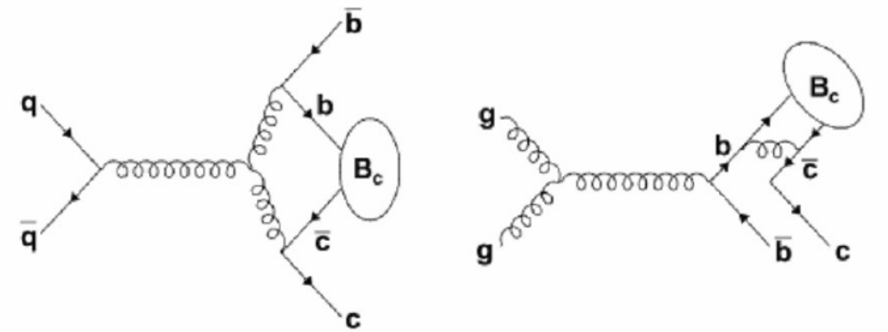
World last measurements

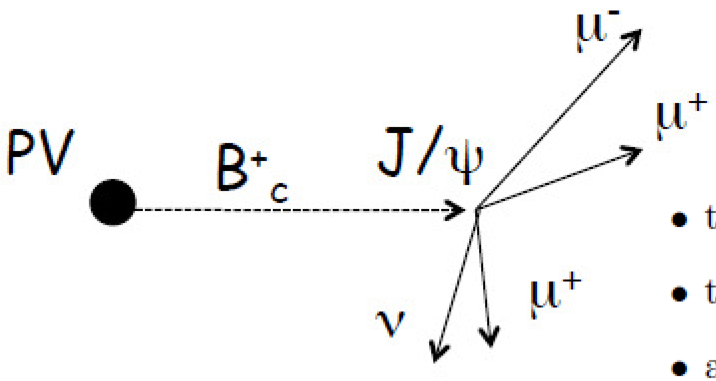


B_c^+ production times *BR* in the J/ψ $\mu^+\nu$ decay mode

First observation at Tevatron run I : Phys.Rev.Lett. 81 (1998) 2432-2437

- B_c meson: a unique laboratory to study QDC and weak decays;
- It decays only weakly and final states with spectator c-quark or b-quark have different final states == > no interference
- The dominant production mode is through hard processes

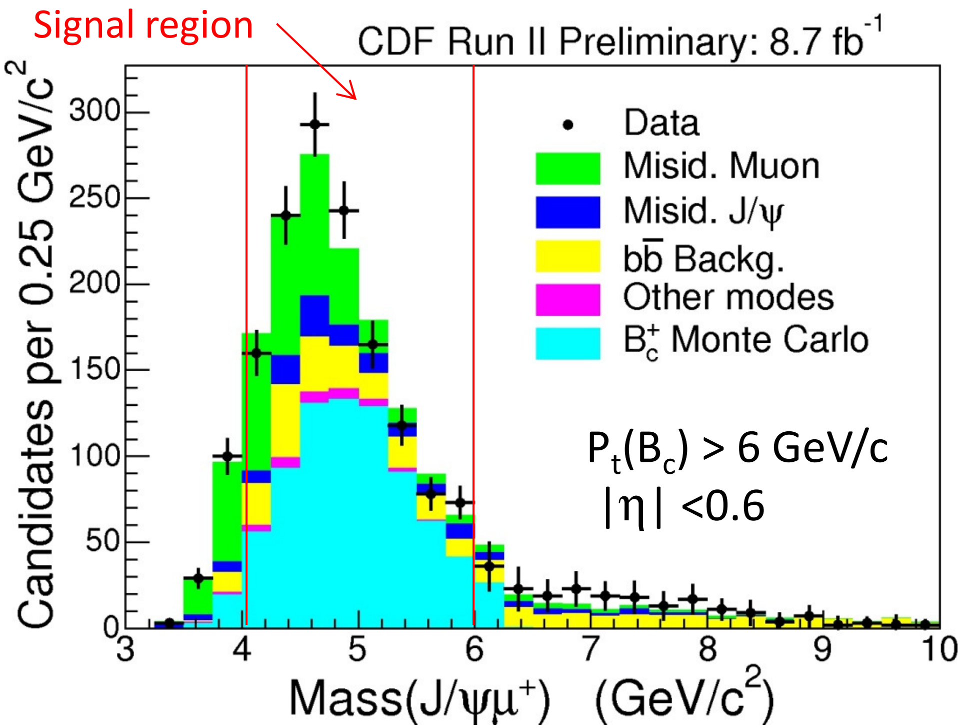




Event selection: associate to the J/Y vertex a third a track that might be:

- the muon in the $B_c^+ \to J/\psi\mu^+X$ decays, or
- the kaon in the $B^+ \to J/\psi K^+$ sample, or
- a π^+, K^+ or p for the misidentified muon background calculation

B_c^+ production times *BR* in the $J/\psi\, \mu^+ \nu$ decay mode



B_c^+ background	Systematic uncertainty
Misidentified J/ψ	not used
Misidentified Muon	$^{+9.6}_{-16.5}$
Double fake	$^{+0.5}_{-0.9}$
$b\bar{b}$ background	± 5.8
Other decay modes	± 16.3
Total	$^{+19.8}_{-23.9}$

	$\Delta\epsilon_{rel}$
B_c^+ lifetime	$^{+0.134}_{-0.147}$
B_c^+ spectrum	$^{+0.356}_{-0.303}$
B^+ spectrum	± 0.055
Tracking eff.	± 0.070
Muon effic.	$^{+0.092}_{-0.087}$
Total systematics	$^{+0.401}_{-0.359}$

Quantity	Value
$N(B_c^+ \to J/\psi\mu^+\nu)$	$739.5 \pm 39.6(\mathrm{stat})\ ^{+19.8}_{-23.9}(\mathrm{sys})$
$N(B^+ \to J/\psi K^+)$	$14338 \pm 125\ (\mathrm{stat})$
ϵ_{rel}	$4.093 \pm 0.038(\mathrm{stat})^{+0.401}_{-0.359}(\mathrm{sys})$

$$\boxed{\frac{\sigma(B_c^+) * BR(B_c^+ \to J/\psi\mu^+\nu)}{\sigma(B^+) * BR(B^+ \to J/\psi K^+)} = 0.211 \pm 0.012\ (\mathrm{stat.})^{+0.021}_{-0.020}\ (\mathrm{syst.})}$$

CDF new result (8.7 fb^{-1})

B meson excited states : phenomenology

- Fine splitting: Light quark spin s couples with L to j of light quark
- Hyperfine splitting: j couples with spin of heavy quark to total angular momentum J

Two states ***narrow*** (parity and angular momentum conservation)

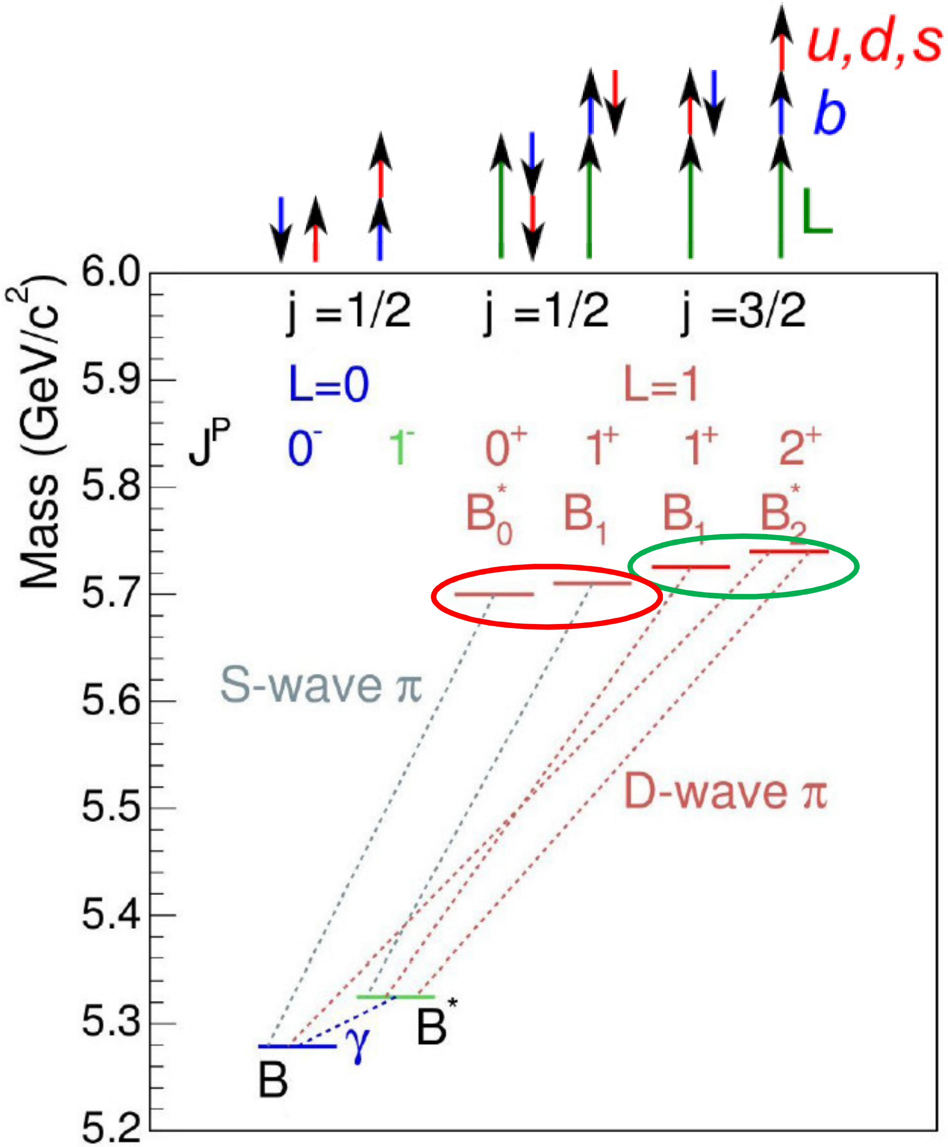
CDF can observe three decays per B meson flavor:

$B_1 \to B^*\pi,\ B_{s1} \to B^*K$

$B_2^* \to B^*\pi,\ B_{s2}^* \to B^*K$

$B_2^* \to B\pi,\ B_{s2}^* \to BK$

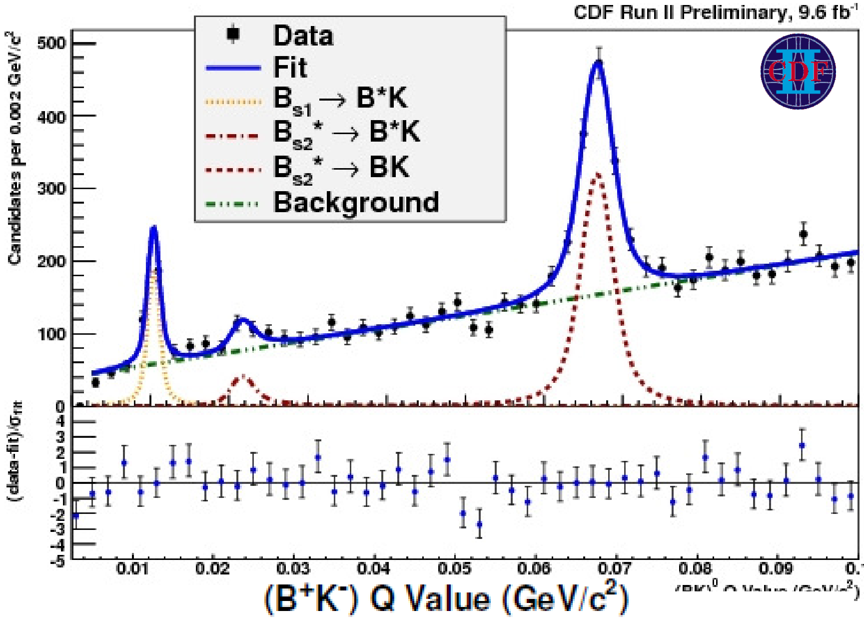
Other two states have predicted widths of 150 MeV/c^2, too broad for CDF



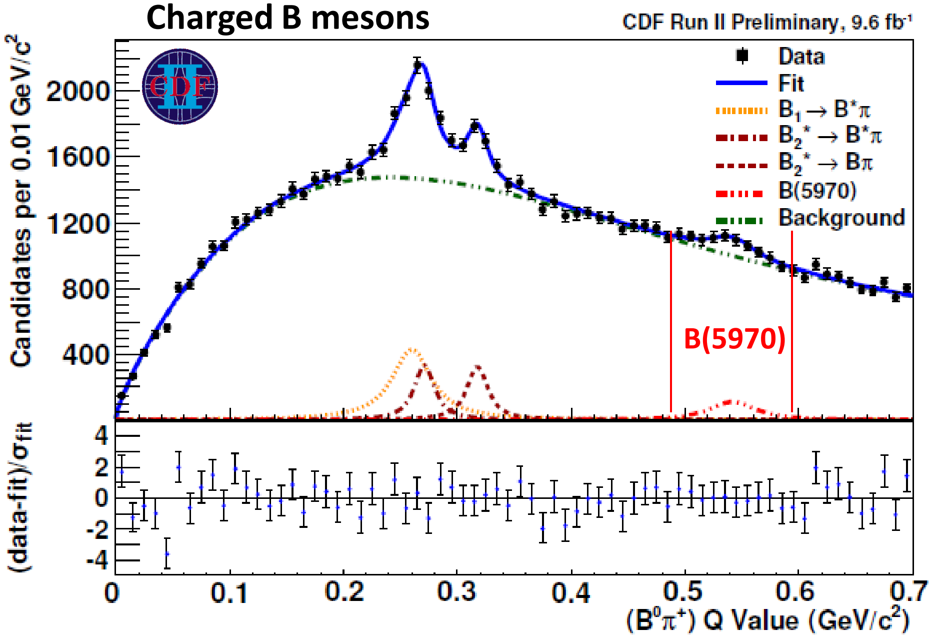
Recent CDF results on B meson excited states

- Two trigger types :
  di-muon for B modes with J/ψ and
  displaced tracks for B modes with D
- Sum of the individual samples with different
  B decay modes (B->J/ψ, B->Dπ, B->D 3π)
- Signals described by non-rel. Breit-Wigner distributions
  convoluted with 2 Gaussians (detector resolution)
- Background described by Γ functions or polynomials

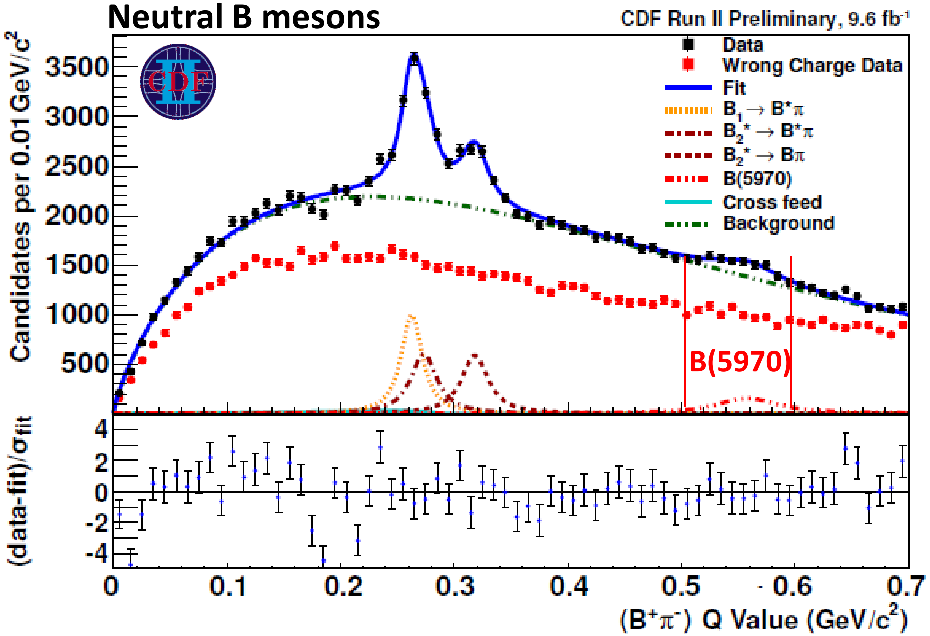
The structure associated to the new resonance B(5970) is observed in excited B^0 and B^+ at the same position



Charged B mesons



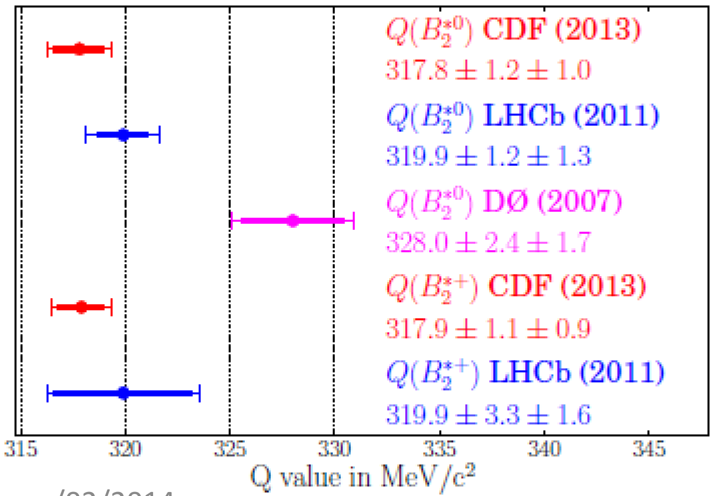
Neutral B mesons



Excited B meson result summary

Calculation	Ref.	$B_1^{0,+}$	$B_2^{*0,+}$	B_{s1}^0	B_{s2}^{*0}
HQET	[3]	5700	5715		
HQET	[4]	5780 ± 40	5794 ± 40	5886 ± 40	5899 ± 49
HQET	[5]	5623	5637	5718	5732
HQET	[6]	5720	5737	5831	5847
HQET	[7]	5719	5733	5831	5844
Lattice	[8]	5732 ± 33	5772 ± 29	5815 ± 22	5845 ± 21
Lattice	[9]			5892 ± 52	5904 ± 52
Potential	[10]	5699	5704	5805	5815
Potential	[11]	5780	5800	5860	5880
HQS	[12]	5755	5767	5834	5846
Chiral theo.	[14]	5774 ± 2	5790 ± 2	5877 ± 3	5893 ± 3
QCD string	[15]	5716	5724		

(Reference list in the back-up)

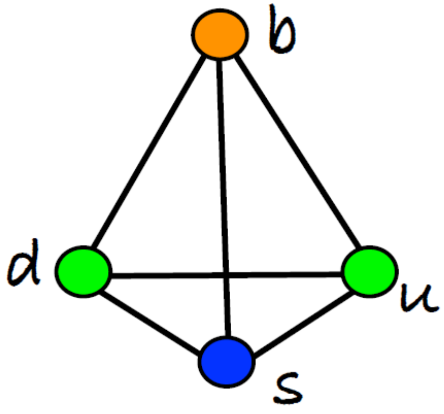


CDF updated results (arXiv:1309.5961)

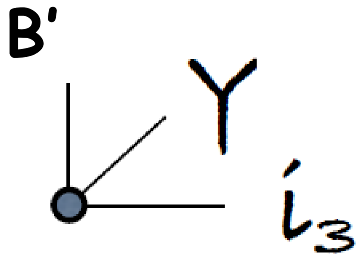
	m (MeV/c^2)
B_1^0	$5726.4 \pm 0.8 \pm 1.3 \pm 0.4$
B_2^{*0}	$5736.6 \pm 1.2 \pm 1.2 \pm 0.2$
B_1^+	$5726 \pm 4 \pm 3 \pm 2$
B_2^{*+}	$5737.1 \pm 1.1 \pm 0.9 \pm 0.2$
B_{s1}^0	$5828.3 \pm 0.1 \pm 0.1 \pm 0.4$
B_{s2}^{*0}	$5839.7 \pm 0.1 \pm 0.1 \pm 0.2$
$B(5970)^0$	$5978 \pm 5 \pm 12$
$B(5970)^+$	$5961 \pm 5 \pm 12$

First evidences of (Bπ) resonances with 4.4 σ significance

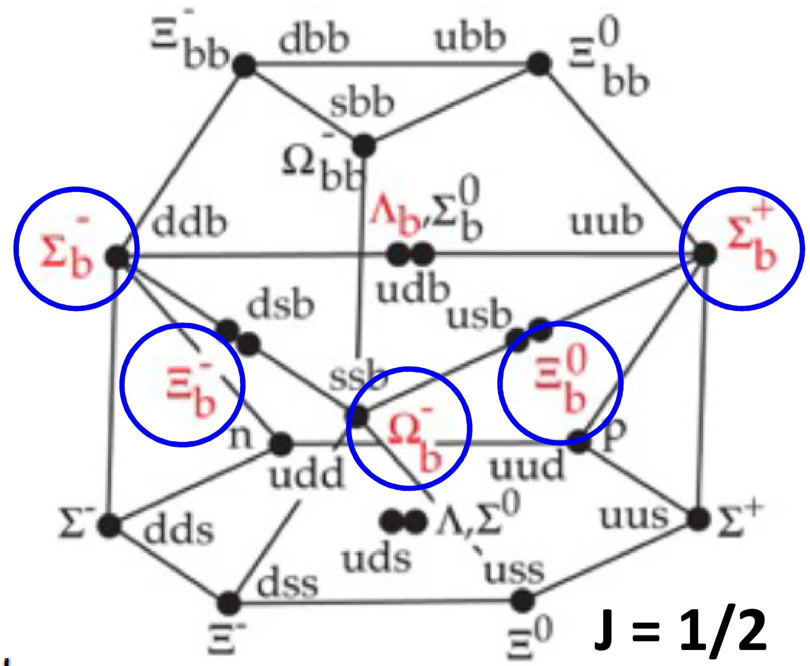
b - baryons



SU(4) u,d,s, b



$$Y = S + B + \frac{B'}{3}$$

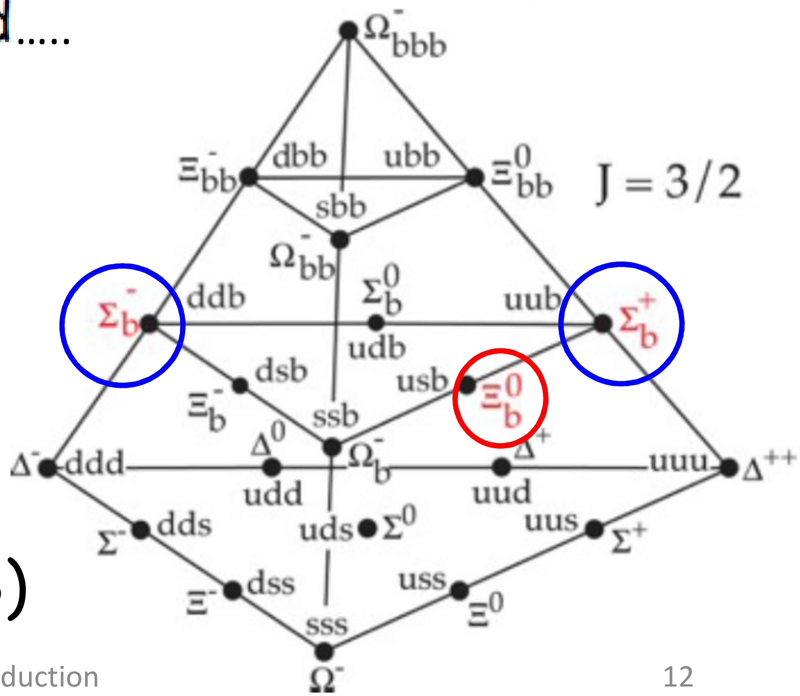


For a long time totally a Tevatron field.....

- $\Sigma_b^{(*)+}$ and $\Sigma_b^{(*)-}$ observed in 2006
- Ξ_b^- observed in 2007
- Ω_b^- observed in 2008
- Ξ_b^0 observed in 2011

.....now a rich legacy to LHC

Ξ_b^0 (5945) observed in 2013 (CMS)



b-baryon decay modes reconstructed at Tevatron

J/Psi modes

$\Lambda_b \to J/\psi\ \Lambda$, $\quad J/\psi \to \mu^+\mu^-$, $\quad \Lambda \to p\ \pi^-$

$\Xi_b^- \to J/\psi\ \Xi^-$, $\quad J/\psi \to \mu^+\mu^-$, $\quad \Xi^- \to \Lambda\ \pi^-$, $\quad \Lambda \to p\ \pi^-$

$\Omega_b^- \to J/\psi\ \Omega^-$, $\quad J/\psi \to \mu^+\mu^-$, $\quad \Omega^- \to \Lambda\ K^-$, $\quad \Lambda \to p\ \pi^-$

2 – 3 cascade vertices

Fully hadronic modes

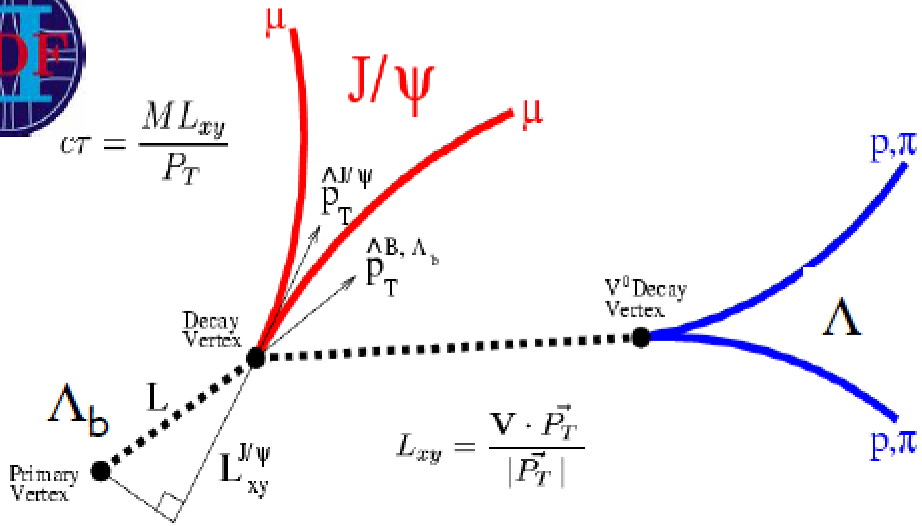
$\Xi_b^- \to \Xi_c^0\ \pi^-$, $\quad \Xi_c^0 \to \Xi^-\ \pi^+$, $\quad \Xi^- \to \Lambda\ \pi^-$, $\quad \Lambda \to p\ \pi^-$

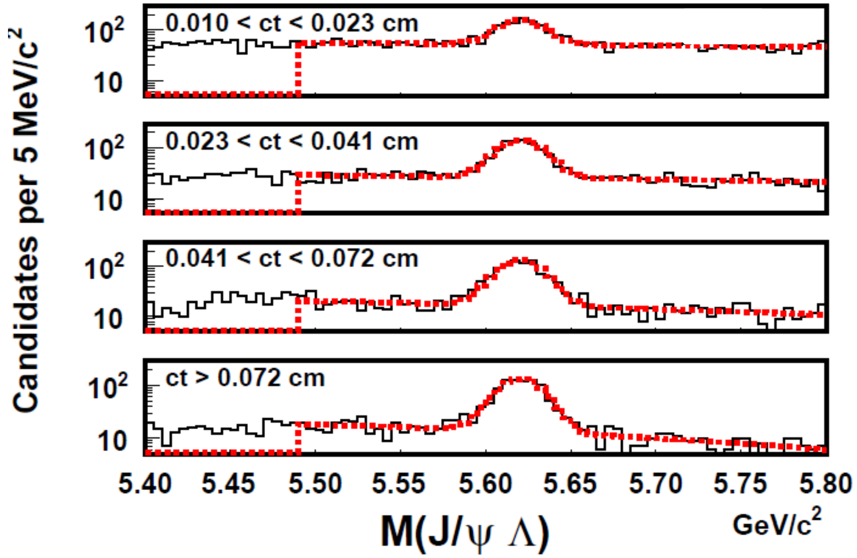
$\Xi_b^0 \to \Xi_c^+\ \pi^-$, $\quad \Xi_c^+ \to \Xi^-\ \pi^+\ \pi^+$, $\quad \Xi^- \to \Lambda\ \pi^-$, $\quad \Lambda \to p\ \pi^-$

$\Omega_b^- \to \Omega_c^0\ \pi^-$, $\quad \Omega_c^0 \to \Omega^-\ \pi^+$, $\quad \Omega^- \to \Lambda\ K^-$, $\quad \Lambda \to p\ \pi^-$ **New!**

4 cascade vertices

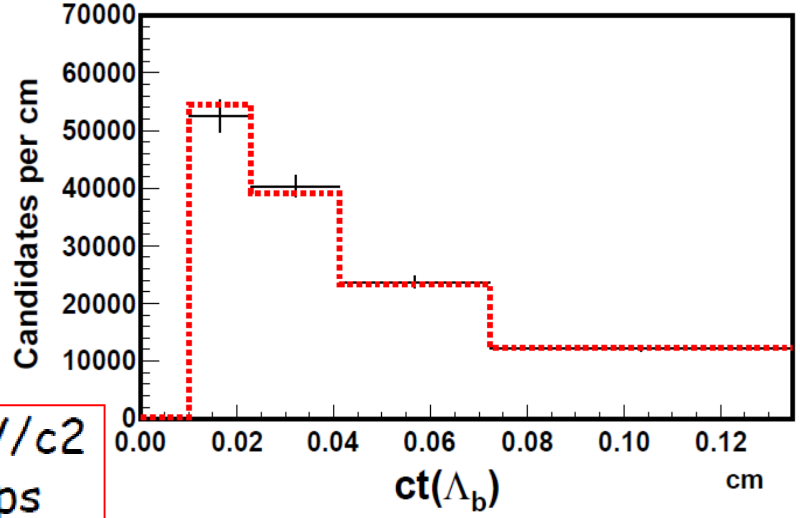
Λ_b mass/lifetime to check the procedure





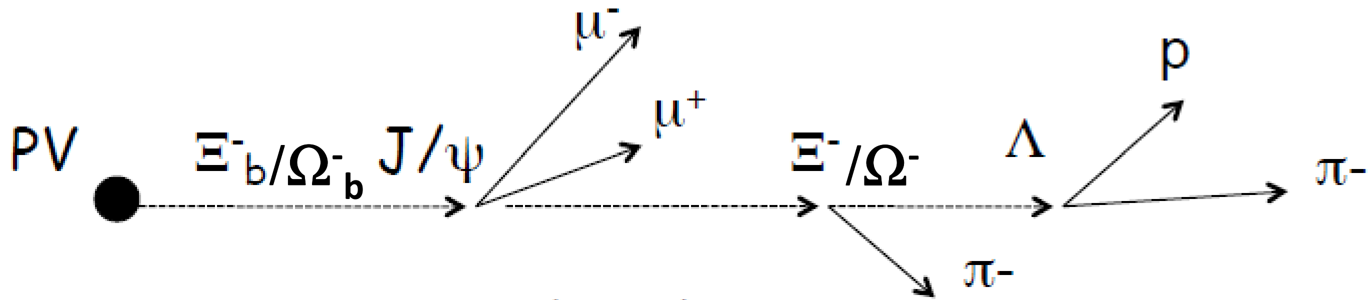
Binned lifetime fit distributions

- Each bin comes from an independent fit to the mass distribution
- Dashed lines are fit projections



Mass (Λ_b): 5620.14 ± 0.31(stat) ± 0.40(syst) MeV/c2
Lifetime (Λ_b): 1.565 ± 0.035(stat) ± 0.020(syst) ps

Ξ^-_b and Ω^-_b mass and lifetime : J/ψ mode

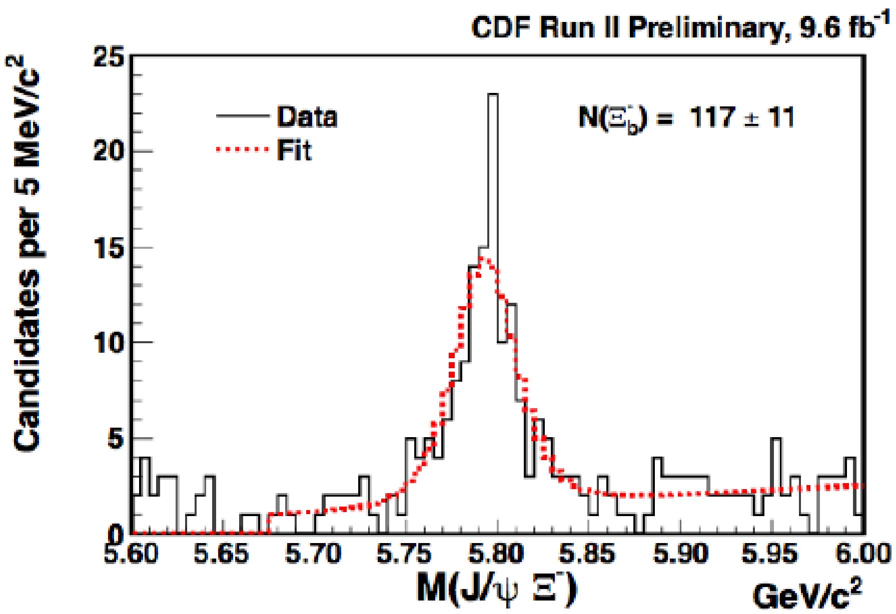


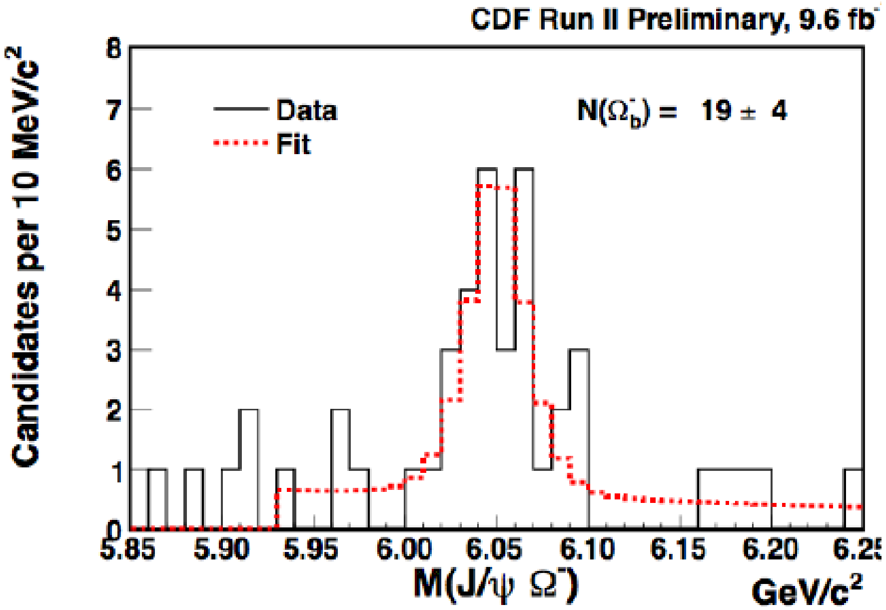
Ξ^-_b Observation PRL 99, 052001 (2007)

Ω^-_b Observation

PRL 101, 232002 (2008)

PRD 80, 072003 (2009)





Phys. Rev. D 89, 072014 (2014)

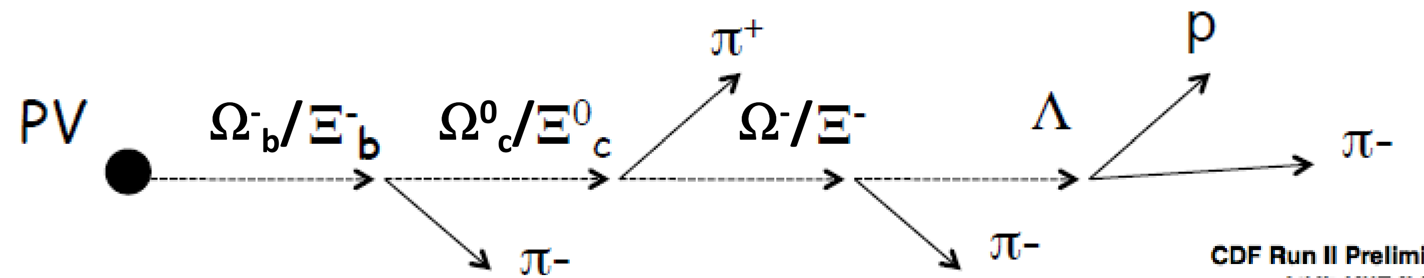
Mass (Ξ^-_b): 5791.6 ± 2.0(stat) ± 0.40(syst) MeV/c^2

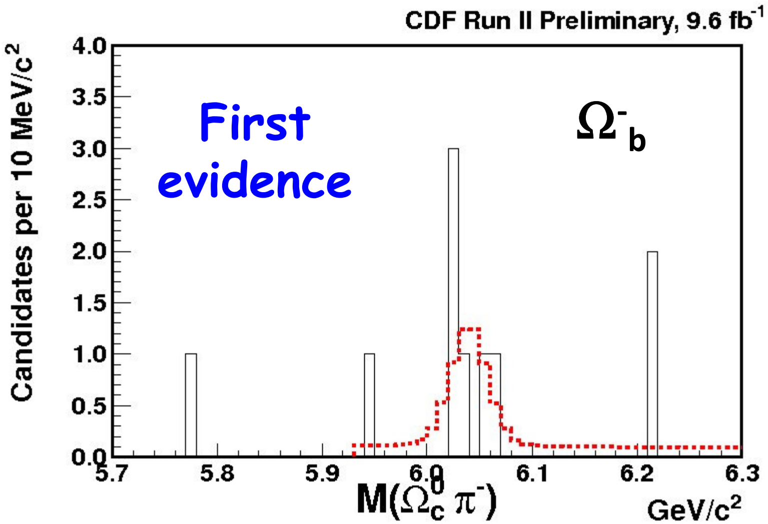
Lifetime (Ξ^-_b): 1.36 ± 0.15(stat) ± 0.02(syst) ps

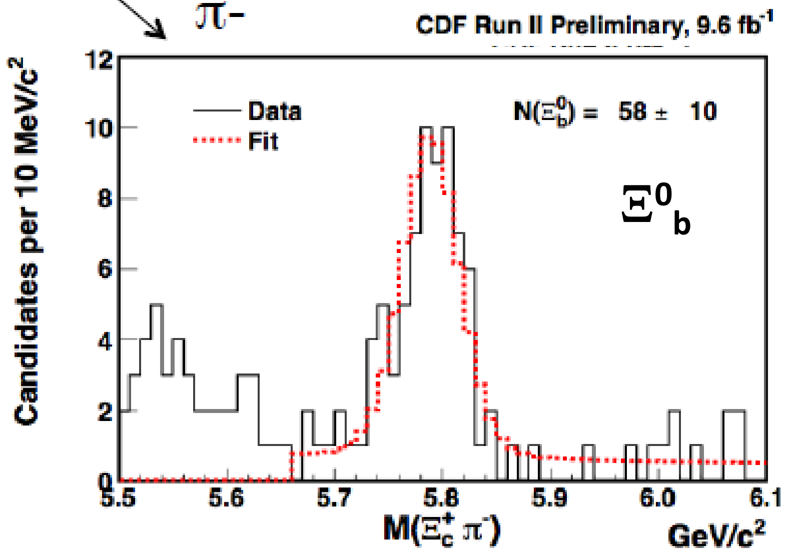
Mass (Ω^-_b): 6051.4 ± 4.2(stat) ± 0.5(syst) MeV/c^2

Lifetime (Ω^-_b): 1.77 +0.55 -0.41(stat) ± 0.02(syst) ps

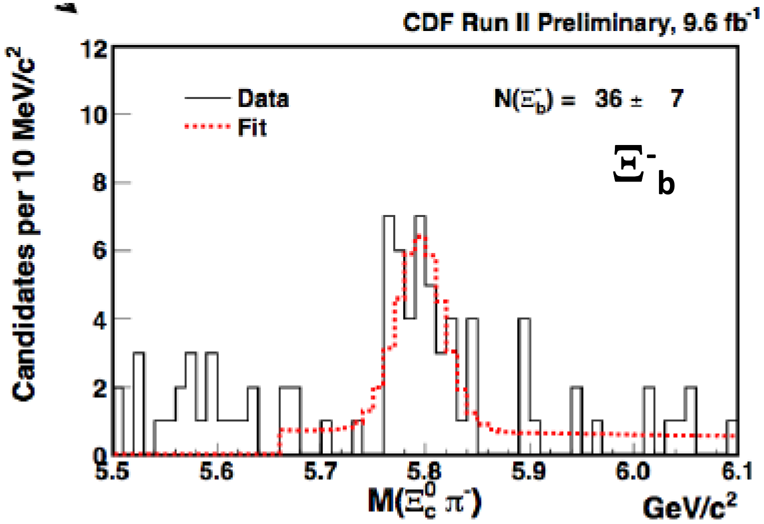
$\Xi^{-(0)}_b$ and Ω^-_b mass and lifetime : full hadronic







Ξ_b^0, Ξ_b^- observation in the hadronic sample
PRL 107, 102001 (2011)



Phys. Rev. D 89, 072014 (2014)

Mass(Ξ^-_b): 5796.5 ±4.7(stat) ±0.95(syst) MeV/c^2

Mass(Ξ^0_b): 5791.6 ±5.0(stat) ±0.73(syst) MeV/c^2

Mass(Ω^-_b): 6040 ±8(stat) ±2(syst) MeV/c^2

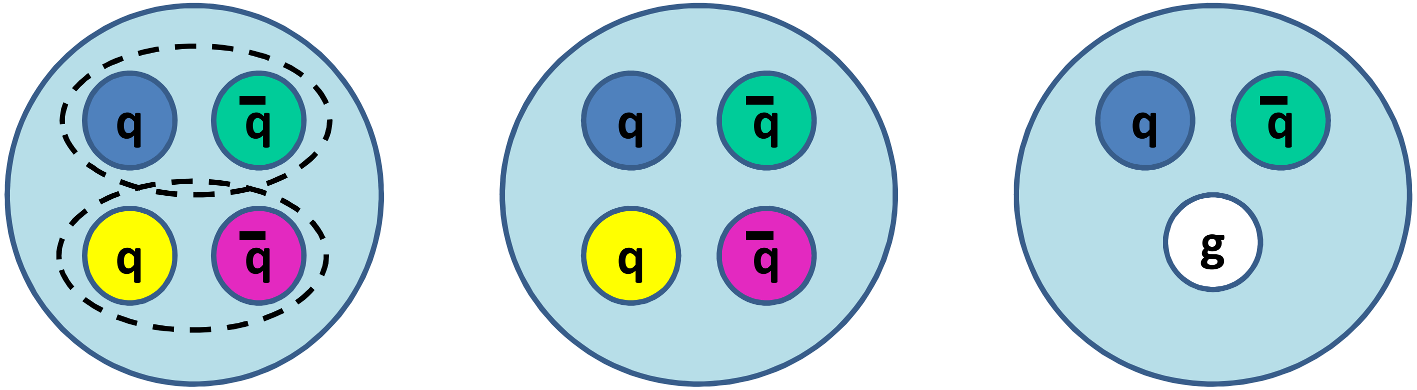
b baryon masses and lifetimes : Tevatron vs LHC

After more than two years from the collision end, b-baryon properties measured at Tevatron are still almost competitive with first LHC results …

	CDF		LHCb	
	Mass (Mev/c²)	**Lifetime (ps)**	**Mass (Mev/c²)**	**Lifetime (ps)**
Λ_b	5620.15 ± 0.31 ± 0.47	1.565 ± 0.035 ± 0.020	5619.53 ± 0.13 ± 0.45	1.482±0.018±0.012
Ξ_b^-	5793.4 ± 1.8 ± 0.7	1.32 ± 0.14 ± 0.02	5795.8 ± 0.9 ± 0.4	$1.55 \pm ^{+0.10}_{-0.09} \pm 0.03$
Ξ_b^0	5788.7 ± 4.3 ± 1.4	--	--	--
Ω_b^-	6047.5 ± 3.8 ± 0.6	$1.66 \pm ^{+0.53}_{-0.40} \pm 0.02$	6046.0 ± 2.2 ± 0.4	$1.54 \pm ^{+0.26}_{-0.21} \pm 0.05$

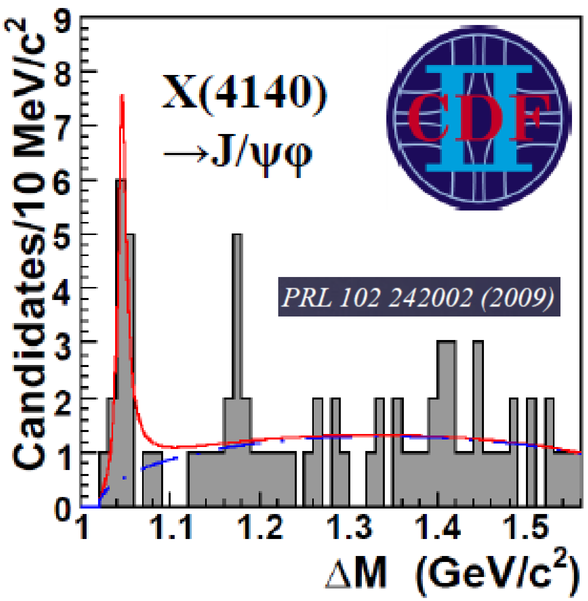
Narrow exotic resonances in the B decay product spectrum

No theoretical reasons to exclude (colorless) bound quark states
other than mesons and baryons



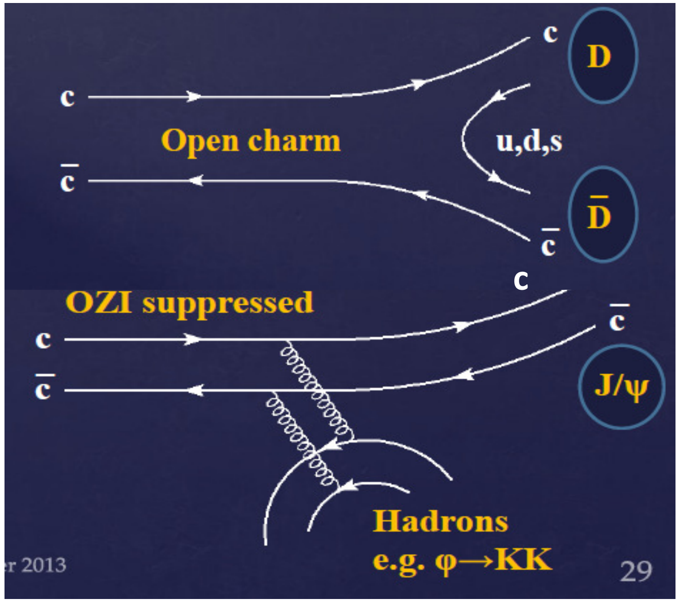
Meson molecule | Tetraquark | Quark-gluon hybrid

No definitive experimental evidence of any such states yet established ….



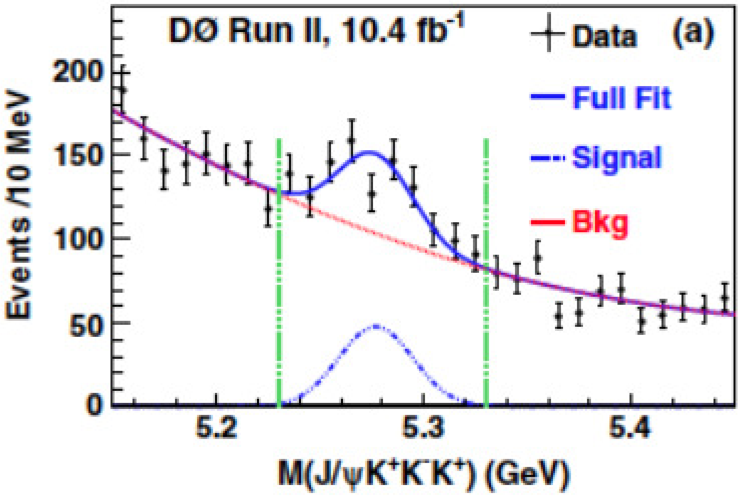
X(4140): intrepretation ?

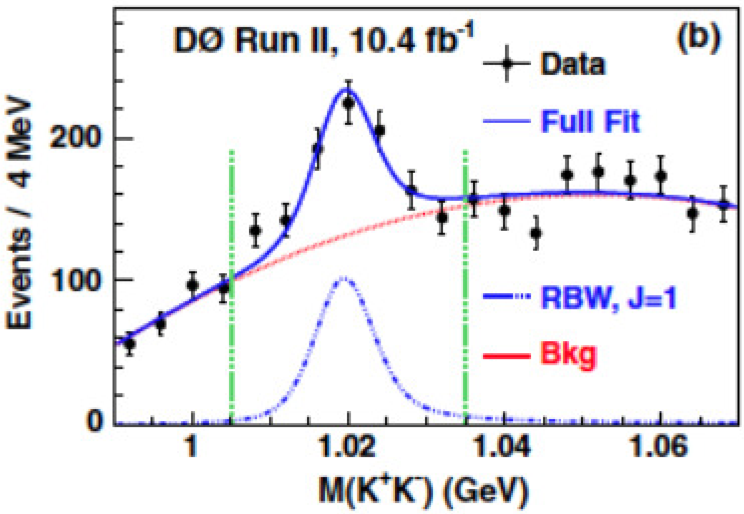
Mass well above the 3730 MeV open charm threshold, conventional charmonium should decay into ($D\bar{D}$)

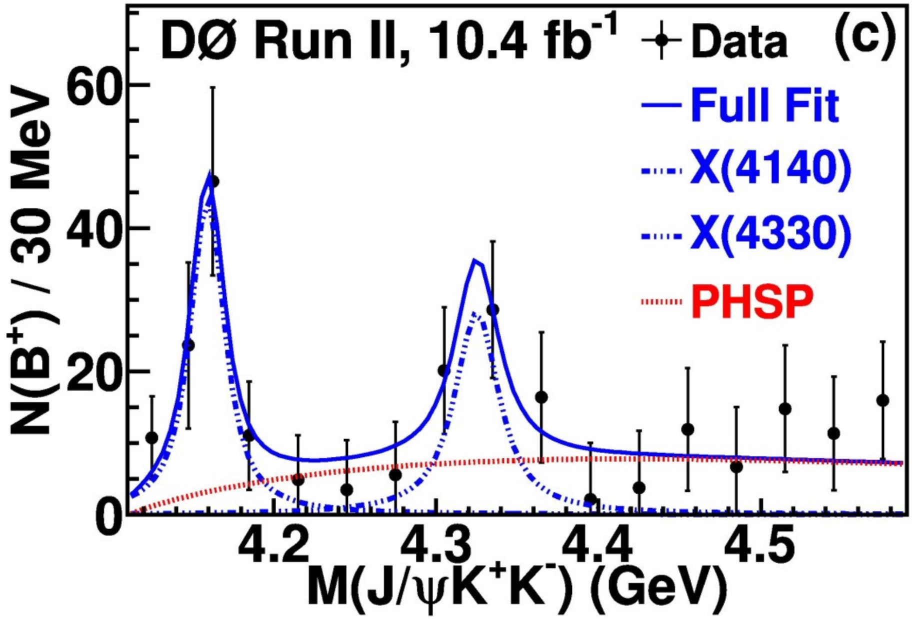


X(4140) search: D0 results summary

Measured 215 ±37 B^+ events







3.1σ evidence for the X(4140)

Mass

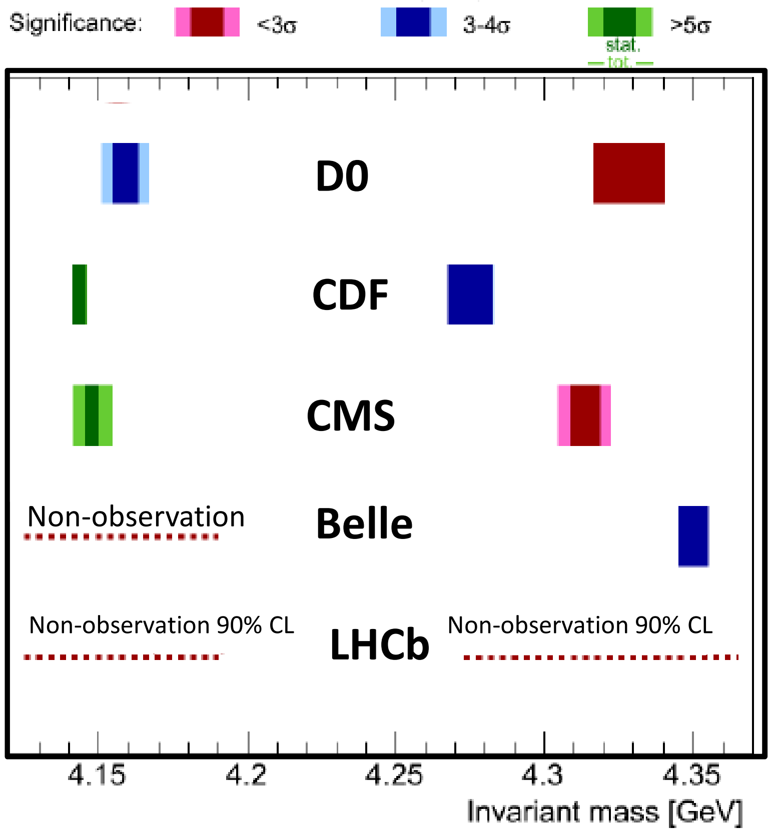
4159 ±4.3(stat) ±6.6(syst) MeV/c^2

Width

19.9 ±12.6(stat) ±8(syst) MeV/c^2

$$\frac{BR(B^+ \to X(4140)K^+)}{BR(B^+ \to J/\psi\phi K^+)} = [19 \pm 7(stat) \pm 4(syst)]\ \%$$

PRD89, 012004 (2014)



Summary of the observation status of the J/ψ ϕ resonances

Debate on the existence of the narrow X(4140) resonance in the J/ψ ϕ spectrum of the $B^+ \to J/\psi\, \phi\, K^+$ dacay not yet closed .....

.... inconsistent results for the resonance around 4300 MeV/c^2

Experiment	Resonance I		Resonance II		Year	Reference
	Mass (MeV/c^2)	significance	Mass (MeV/c^2)	significance		
Belle	Non-observation		$4350.6^{+4.6}_{-5.1} \pm 0.7$	3.2 σ	2009	PRL 104 112004 (2010)
CDF	$4143.4^{+2.9}_{-3.0} \pm 0.6$	> 5 σ	$4274.4^{+8.4}_{-6.7}$	3.1 σ	2011	arXiv:1101.6058
LHCb	Non-observation		Non-observation		2012	PRD 85 091103(R) (2012)
D0	$4159.0 \pm 4.3 \pm 6.6$	3.1 σ	4329	1.7 σ	2013	PRD 86 112004 (2014)
CMS	$4148.0 \pm 2.4 \pm 6.3$	> 5 σ	$4313.8 \pm 5.3 \pm 7.3$	< 3 σ	2013	arXiv:1309.6920

Conclusions

- Tevatron experiments produced high qualitity results in heavy flavor physics during the last two decades, more than 150 paper published.

- The results have been complentary and competitve with the B-factories, showing that precision heavy flavor physics is possible at the hadron colliders.

- Many tools and methods were developped for a clean identification of events with b-hadron production; a rich legacy is left to LHC and to the future B-factories.

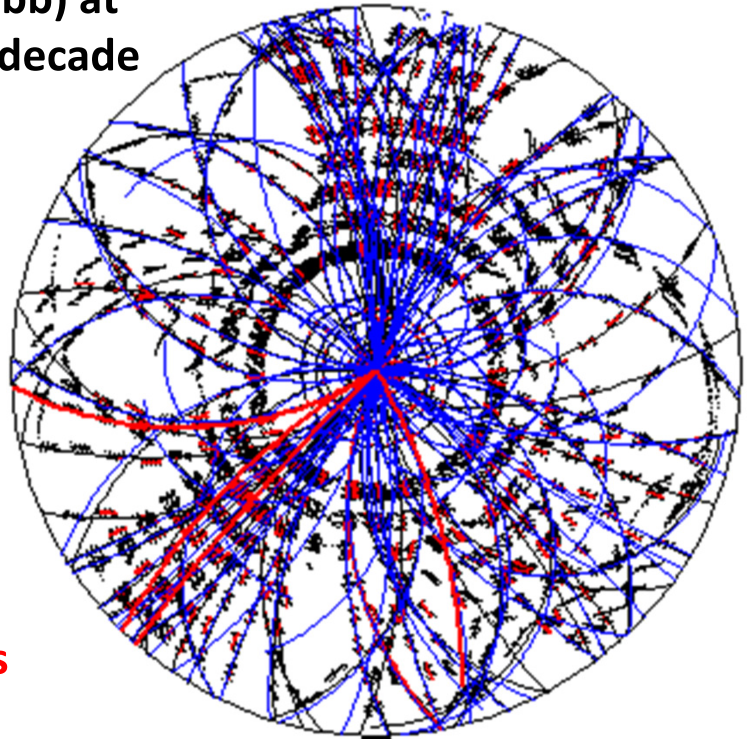
- The analysis of the full statistics samples collected by CDF and D0 is not yet completed; possible interesting results could still be obtained …..

Back-up

Heavy Flavor Production at Tevatron

$\sigma(p\bar{p} \to b\bar{b})$ at Tevatron $O(10^4\text{-}10^5)$ larger than $\sigma(e^+e^- \to b\bar{b})$ at the B-factories [Υ(4s)] active in the same data taking decade

	$\sqrt{s}$	Process	X-section
B-Factories	10 GeV	e^+e^- -> b bbar	1000 pb
Tevatron	2 TeV	p pbar -> b bbar	50 μb
LHC	8 TeV	p p -> b bbar	200 μb



-- all b-hadrons (B^+, B^0, B_s, B_c, Λ_b, Σ_b, Ξ_b , Ω_b) are produced with production fractions

$$f_d : f_u : f_s : f_\Lambda \sim 4 : 4 : 1 : 1$$

-- physics program complementary to the B-Factories

Fine, but…

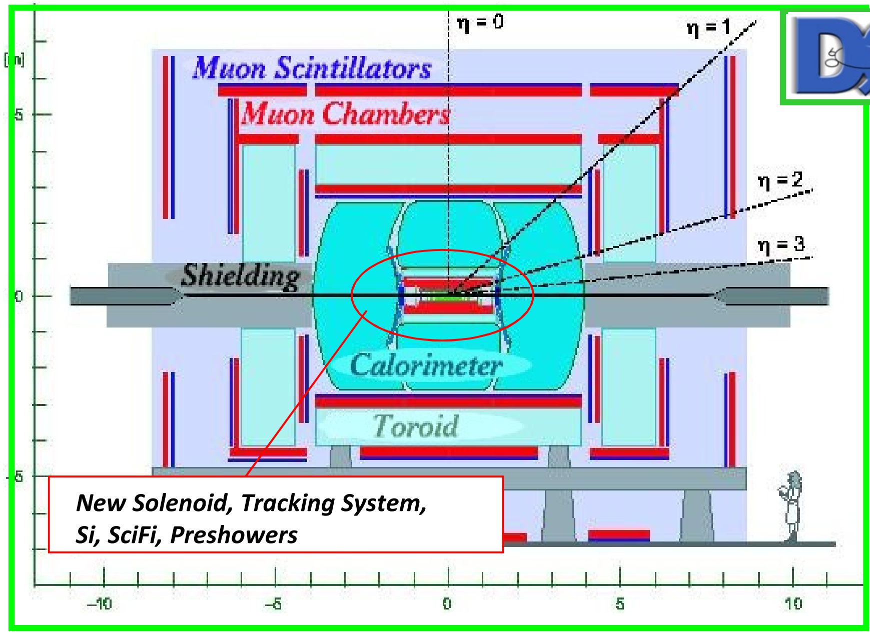
- $\sigma(pp)_{inel.}$ ~ 100 mb is a factor 10^3-10^4 larger than $\sigma(b\bar{b})$
- The BRs of rare b-hadron decays are $O(10^{-6})$ or lower

therefore…..

Detectors need to have:

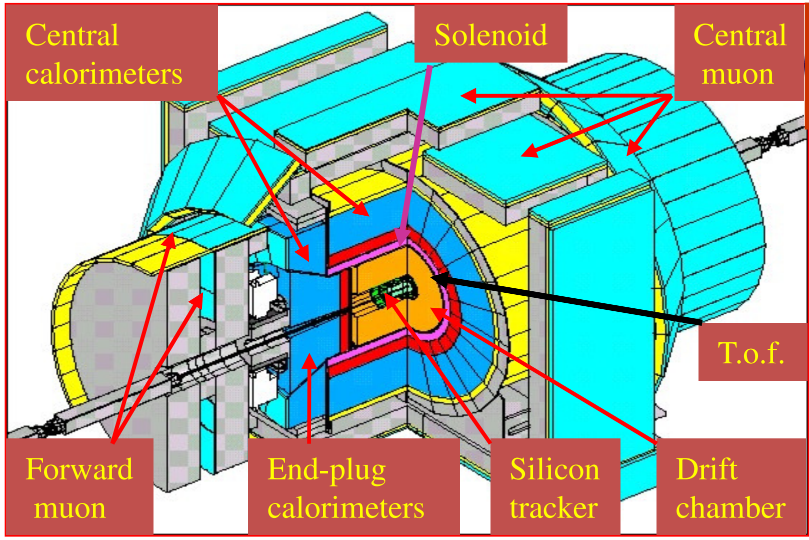
- Very good tracking and vertex resolution
- Wide acceptance and good ID for electrons and muons
- Highly selective trigger

Tevatron run II detectors: a 10 year high performance continuous operation



Both detectors:

- Silicon μ–vertex
  - CDF: L00 (r_{inner}~1.4cm)
  - DØ:L0 upgrade (r_{inner}~1.6cm)
- Central tracking in solenoid
- Calorimeters and muon system
- High rate trigger/DAQ



DØ

- Good electron, muon ID and acceptance
- Excellent tracking acceptance $|\eta| < 2$ (3)
- Thick shielding before muon system suppresses punchthrough

CDF

- L2 trigger on displaced vertices [$\sigma(d_0)$~48 μm]
- Excellent tracking resolution [$\sigma(p_T)/p_T^2$ ~0.15% GeV^{-1}]
- Good low momentum PID

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D0 event selection criteria for the $B^+ \to J/\psi\ \phi\ K^+$ mode

1) Require two muons of opposite charge

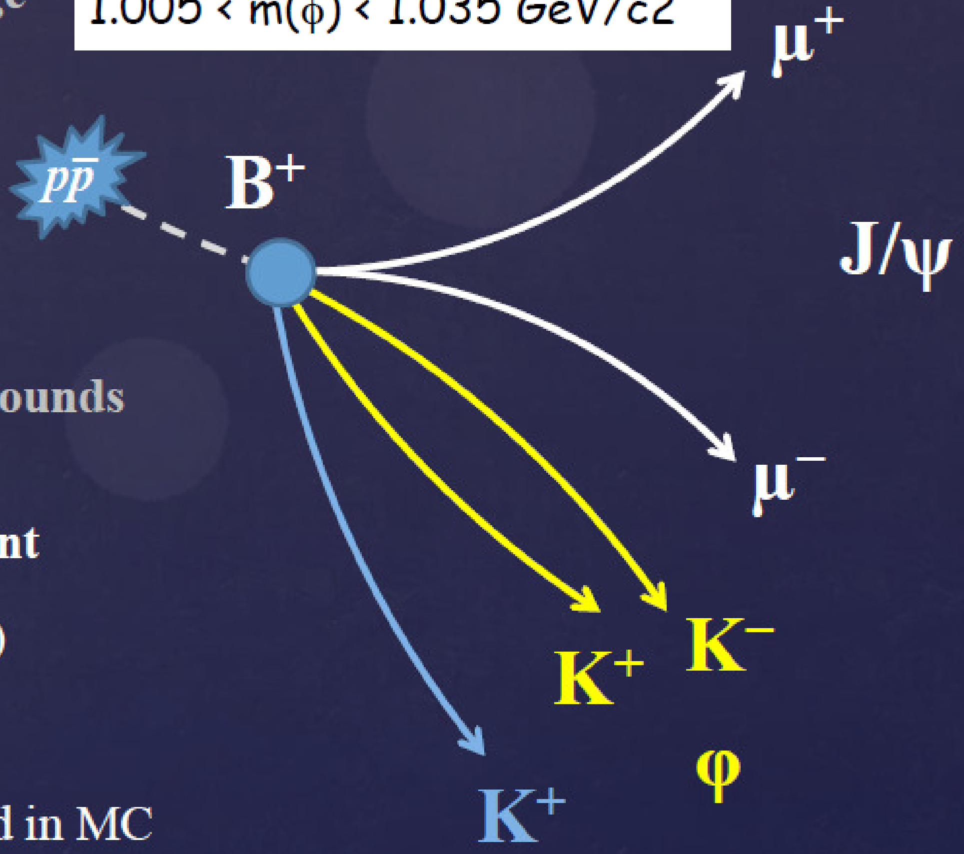
2) Require two tracks of opposite charge

3) Combine with additional track

4) Reconstruct B^+ candidate

5) Apply cuts to remove physics backgrounds

$L_{xy}(B^+) > 250\ \mu m$
$p_T(B^+) > 7\ GeV/c$
$d(J/\psi\phi) < 50\ \mu m$
$1.005 < m(\phi) < 1.035\ GeV/c2$



6) Choose best single candidate per event

- Pick candidate with lowest $M(\varphi \to KK)$
- 95% efficient for signal
- Possible sampling bias tested/corrected in MC